Evidence for a Goldstone Mode in a Double Layer Quantum Hall System

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The tunneling conductance between two parallel 2D electron systems has been measured in a regime of strong interlayer Coulomb correlations. At total Landau level filling $\nu_T = 1$ the tunnel spectrum changes qualitatively when the boundary separating the compressible phase from the ferromagnetic quantized Hall state is crossed. A huge resonant enhancement replaces the strongly suppressed equilibrium tunneling characteristic of weakly coupled layers. The possible relationship of this enhancement to the Goldstone mode of the broken symmetry ground state is discussed.

When two parallel two-dimensional electron systems (2DES) are sufficiently close together, interlayer Coulomb interactions can produce collective states which have no counterpart in the individual 2D systems [1–3]. One of the simplest, yet most interesting, examples occurs when the total electron density, N_T, equals the degeneracy eB/h of a single spin-resolved Landau level produced by a magnetic field B. In the balanced case (i.e. with layer densities $N_1=N_2=N_T/2$), the Landau level filling factor of each layer viewed separately is $\nu = hN_T/2eB=1/2$. If the separation d between the layers is large, they behave independently and are well described as gapless composite fermion liquids. No quantized Hall effect (QHE) is seen. On the other hand, as d is reduced, the system undergoes a quantum phase transition [4–6] to an incompressible state best described by the total filling factor $\nu_T=1/2+1/2=1$. A quantized Hall plateau now appears at $\rho_{xy} = h/e^2$. Both Coulomb interactions and interlayer tunneling contribute to the strength of this QHE but there is strong evidence from experiment [3,7] and theory [1,8] that the incompressibility survives in the limit of zero tunneling. This remarkable collective state exhibits a broken symmetry [9–11], spontaneous interlayer phase coherence, and may be viewed as a new kind of easy-plane ferromagnet. The magnetization of this ferromagnet exists in a pseudospin space; electrons in one layer are pseudospin up, while those in the other layer are pseudospin down. Numerous interesting properties are anticipated, including linearly dispersing Goldstone collective modes (i.e. pseudospin waves), a finite temperature Kosterlitz-Thouless (K-T) transition, dissipationless transport for currents directed oppositely in the two layers, and bizarre topological defects in the pseudospin field [9–12]. To date, most experimental results on this system have derived from electrical transport measurements [3,4,7,13,14] although recently an optical study has been reported [15].

In this paper we report a new study of the double layer $\nu_T=1$ ferromagnetic quantum Hall state, and its transition at large layer separation to a compressible phase, using the method of tunneling spectroscopy. Earlier experiments have shown that there is a very strong suppression of the equilibrium tunneling between two widely separated parallel 2DESs at high magnetic field [16,17]. This suppression is a result of the energetic penalty accompanying the rapid injection (or extraction) of an electron into the strongly correlated electron system produced by Landau quantization. Other than a small downward shift in energy produced by the excitonic attraction of a tunneled electron and the hole it leaves behind in the source layer [18], the measured tunneling spectrum is simply a convolution of the spectral functions in the individual layers. Here we show that when the layers are close enough together to support the bilayer $\nu_T=1$ QHE state, this is no longer the case. The strong suppression is replaced by a huge resonant enhancement of the tunneling. The appearance of this resonance suggests the existence of a soft collective mode of the double layer system which enhances the ability of electrons to tunnel. This may well be the predicted [9,10] Goldstone mode of the broken symmetry ferromagnetic ground state at $\nu_T=1$.

The samples used in this experiment are GaAs/Al$_x$Ga$_{1-x}$As double quantum well (DQW) heterostructures grown by molecular beam epitaxy (MBE). Two 180Å GaAs quantum wells are separated by a 99Å Al$_{0.9}$Ga$_{0.1}$As barrier layer. The DQW is embedded in thick Al$_{0.3}$Ga$_{0.7}$As layers which contain Si doping sheets set back from the GaAs wells sufficiently far to produce 2D electron gases in each well with nearly equal electron densities of $5.4 \times 10^{10} cm^{-2}$. A square mesa, $250\mu m$ on a side, is patterned using standard photolithography. Gate electrodes deposited above and below this mesa allow control over the densities $N_{1,2}$ of the two 2D layers. The low temperature mobility of the as-grown sample is $7.5 \times 10^5 cm^2/Vs$ but this drops to $2.5 \times 10^5 cm^2/Vs$ when the layer densities are reduced to $2 \times 10^{10} cm^{-2}$. Ohmic contacts are placed at the ends of four arms extending outward from the central mesa. Using a selective depletion scheme [19], these contacts can be connected to both 2D layers in parallel or to either layer individually. Consequently, both conventional resistivity and interlayer tunneling measurements can be made on the same sample during a single cooldown from room temperature. Qualitatively identical tunneling data were obtained from three distinct samples taken from the same MBE wafer.
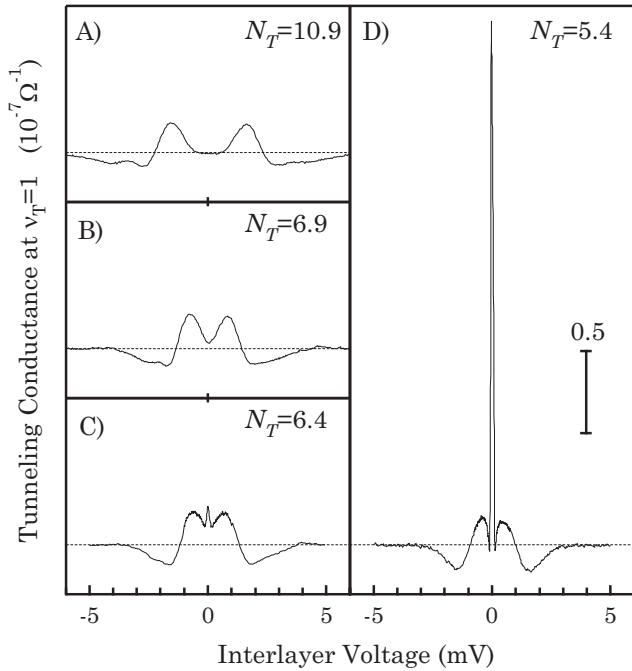
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FIG. 1. Tunneling conductance dI/dV vs. interlayer voltage V at $\nu_T = 1$ and T=40mK in a balanced double layer 2D electron system. Each trace corresponds to a different total density N_T (in units of $10^{10}cm^{-2}$), and thus a different magnetic field. Trace A, at the highest density, shows a deep suppression of the tunneling near zero bias. By trace D, the lowest density of the four shown, this suppression has been replaced by a tall peak. The vertical scale is the same for all traces.

At zero magnetic field and low temperature the tunneling current-voltage (I-V) characteristics of our samples exhibit the simple sharp resonances characteristic of a high degree of momentum and energy conservation upon tunneling [20]. The tunneling conductance dI/dV exhibits a sharp peak which, for equal layer densities, is centered at zero interlayer bias voltage V. The width of this peak ranges from 0.15meV for $N_1 = N_2 = 5.4 \times 10^{10}cm^{-2}$ to about 0.2meV at $2.1 \times 10^{10}cm^{-2}$ and reflects the static disorder in the system [20]. The peak conductance is typically only about $3 \times 10^{-8}\Omega^{-1}$. The samples were designed to be weakly tunneling in order to avoid problems arising from the small sheet conductivities of the 2D layers which develop at high magnetic field.

Figure 1 displays the central result of this investigation. Four low temperature (T=40mK) tunneling conductance spectra are shown, each at a different total density N_T in the bilayer system. In each case the individual layer densities were carefully matched by adjusting (via the gates) the symmetry and voltage location of the tunnel resonance at zero magnetic field. The traces were taken at different magnetic fields but each represents total Landau level filling factor $\nu_T = 1$. For trace A the density is relatively high, $N_T = 10.9 \times 10^{10}cm^{-2}$, and the well-known coulombic suppression of tunneling at the Fermi level (i.e. at $V=0$) is clearly evident [16,17]. Trace B, taken at $N_T = 6.9 \times 10^{10}cm^{-2}$, is similar to A except that the suppression effect is weaker and the overall spread in energy of the tunneling is less. This is the expected behavior since the inter-particle Coulomb energy falls with density. Trace C, at $N_T = 6.4 \times 10^{10}cm^{-2}$, reveals a qualitatively new feature: a small yet sharp peak in dI/dV at $V = 0$. Finally, at the still lower density $N_T = 5.4 \times 10^{10}cm^{-2}$, trace D shows that the peak has become enormous and dwarfs all other features in the tunnel spectrum. The height of this peak continues to grow as the density is reduced to $3.2 \times 10^{10}cm^{-2}$ where it exceeds even the zero magnetic field tunneling conductance by more than a factor of 10 [21].

It is important to note that while the two layers have equal densities at $V = 0$, the finite interlayer capacitance disrupts this balance at non-zero V. For the data in Fig. 1, this effect preserves $\nu_T = 1/2 + 1/2 = 1$ since carriers are merely shifted from one layer to the other. We have found it possible to compensate for this effect, i.e. maintain the individual layers at fixed density, by adjusting the top and bottom gate voltage in linear proportion to the interlayer voltage V. This compensation alters the details of the tunneling characteristic at large V, but it has a negligible effect near $V = 0$. Since our primary focus is the resonant peak at $V = 0$, we shall for simplicity restrict the subsequent discussion to data obtained without compensating for the capacitive charge transfer.

Figure 2 shows the magnetic field dependence of the zero bias (i.e. $V = 0$) tunneling conductance G_0, at T=40mK, for $N_T = 10.9 \times 10^{10}$ and $4.2 \times 10^{10}cm^{-2}$. In order to directly compare the two curves, the data is plotted against the inverse total filling factor $\nu_T^{-1} = eB/hN_T$, instead of magnetic field. As expected, both curves exhibit quantum oscillations of the tunneling conductance at small magnetic field. These oscillations are less pronounced in the low density data owing to the reduced electron mobility. At high magnetic field, in the vicinity of $\nu_T = 1$, the two data sets differ qualitatively. The high density data show that for magnetic fields above about $\nu_T^{-1} \approx 0.3$, the tunneling conductance is near zero. This again is the coulombic suppression characteristic of tunneling between two weakly coupled 2D electron systems at high magnetic field. By contrast, the low density data show an enormous enhancement of the tunneling around $\nu_T = 1$. The enhancement appears strongest at, or very near, $\nu_T = 1$, but it is clearly a very substantial effect over a wide range of filling factors.

The temperature dependence of the zero bias tunneling conductance is displayed in Fig. 3. Two sets of data are shown, one for $N_T = 10.9 \times 10^{10}cm^{-2}$ and one for $N_T = 4.2 \times 10^{10}cm^{-2}$. There is again a qualitative difference between the tunneling at high and low density.

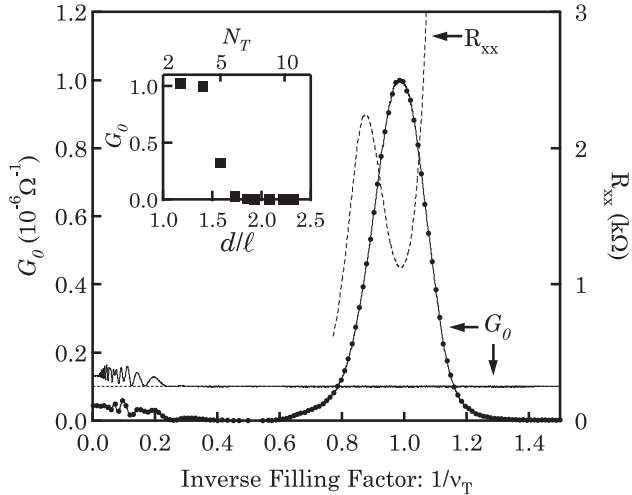FIG. 2.   Zero bias tunneling conductance G_0 vs. inverse filling factor at high and low density. Light solid trace: $N_T = 10.9 \times 10^{10} cm^{-2}$; data displaced vertically for clarity. Above about $\nu_T^{-1} = 0.3$ the conductance is nearly zero. Dotted trace: $N_T = 4.2 \times 10^{10} cm^{-2}$. A huge enhancement of the tunneling is observed near $\nu_T = 1$. Dashed curve: Longitudinal resistance R_{xx} for $N_T = 4.2 \times 10^{10} cm^{-2}$ showing QHE minimum at $\nu_T = 1$. Inset: Tunneling conductance at $\nu_T = 1$ vs. d/ℓ. All data taken at T=40mK.
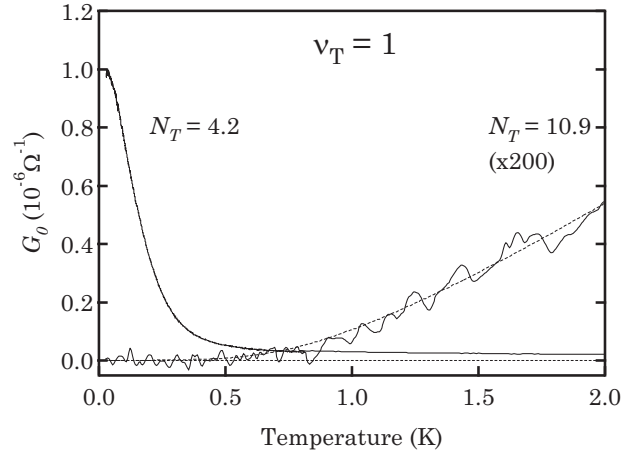

FIG. 3.   Temperature dependence of the zero bias tunneling conductance at $\nu_T = 1$ at high and low densities. Note that the high density data has been magnified by a factor of 200.

At high density the conductance falls with decreasing temperature. As reported previously, this dependence is consistent with simple thermal activation [16]. The low density data behave in the opposite fashion, rising as the temperature falls. The rise becomes fairly steep around T=0.4K and then levels off below about 40mK.

Magneto-transport measurements on similar double quantum well samples have established the approximate location of the phase boundary between the incompressible $\nu_T = 1$ quantized Hall phase and the compressible non-quantized Hall phase at large layer separation [7]. In the limit of weak tunneling this boundary was found to be near $d/\ell \approx 2$. In this ratio d is the center-to-center distance between the quantum wells and $\ell = (\hbar/eB)^{1/2}$ is the magnetic length. In its as-grown state, i.e. when $N_T = 10.9 \times 10^{10} cm^{-2}$, the present sample has $d/\ell = 2.4$ at $\nu_T = 1$. Reducing the density via gating to $N_T = 4.2 \times 10^{10} cm^{-2}$, gives $d/\ell = 1.45$. Control over the layer densities thus allows us to span the expected phase boundary using a single sample. The inset to Fig. 2 shows the zero bias tunneling conductance G_0 at $\nu_T = 1$, at T=40mK, versus d/ℓ. There is a sharp transition near $d/\ell \approx 1.8$ separating two very different tunneling regimes. For $d/\ell > 1.8$ the zero bias conductance is suppressed and the tunneling spectra are qualitatively the same as seen in samples having negligible interlayer correlations. On the other hand, as d/ℓ falls

below this critical value a resonant enhancement of the tunneling appears at zero bias. The magnitude of this peak grows continuously as d/ℓ falls [21].

The rough agreement between the critical d/ℓ value found in transport experiments [7] and that reported here in tunneling studies suggests that they reflect the *same* phase transition. To investigate this, resistivity measurements were performed on the sample. As anticipated, a quantized Hall effect does develop at low density. The dotted trace in Fig. 2 shows the observed minimum in ρ_{xx} at $N_T = 4.2 \times 10^{10} cm^{-2}$ and T=40mK. The relative weakness of this many-body integer QHE may simply be due to the low mobility of the sample ($\sim 2 \times 10^5 cm^2/Vs$) at this reduced density. A second possibility is more interesting: It is well known that for some interaction-driven quantized Hall states Arrhenius behavior of the resistivity ρ_{xx} is not observed until the temperature is reduced well below the measured activation energy. For example, in conventional single layer 2D systems at $\nu = 1$, spin flip activation energies of order 40K are common, but can only be observed at temperatures below a few Kelvin [22]. This effect originates in the low energy of long wavelength spin waves in the system. The activation energy measured in transport reflects the large exchange contribution to the energy required to create a well-separated quasiparticle-quasihole pair. By contrast, at long wavelengths the collective mode energy is the much smaller bare Zeeman energy. Thermal population of large numbers of these modes is apparently effective in suppressing the onset of a thermally activated resistivity. The same phenomenon is observed in the $\nu_T = 1$ QHE in double layer systems [7,13]. Now, however, the collective modes are the predicted pseudospin waves. At $q = 0$

these modes are gapless, but only in the non-physical limit of zero tunneling. In real samples a gap at $q = 0$ is expected, the size of which is determined by both the single particle tunneling energy Δ_{SAS} and an interlayer capacitive charging energy [10,11]. Using our estimate [23] of $\Delta_{SAS} = 90\mu K$ and published [11] estimates of the charging energy, the long wavelength pseudospin wave energy is only about 70mK. It is therefore not so surprising that the ρ_{xx} minimum at $\nu_T = 1$ is weak at 40mK and absent above about 200mK. We note in passing that the estimated Δ_{SAS} in our sample is only 1.3×10^{-6} of the typical Coulomb energy $e^2/\epsilon\ell$ at $N_T = 4.2 \times 10^{10} cm^{-2}$. This is by far the smallest tunneling strength of any sample reported exhibiting the $\nu_T = 1$ bilayer QHE state.

A qualitative explanation for the tunneling enhancement reported here can be constructed from known aspects of double layer systems at $\nu_T = 1$. At high densities, when the layers are weakly coupled, the zero bias tunneling is heavily suppressed. The energetic penalty associated with tunneling in this case arises because an electron attempting to tunnel is totally "unaware" of the strong correlations present within the layer it is about to enter. In the $\nu_T = 1$ bilayer QHE state just the opposite is true; the very essence of the state lies in the strong interlayer correlation it contains. Indeed, the so-called Ψ_{111} wavefunction [1,8] believed to represent this QHE state may be viewed as a collection of correlated interlayer excitons. An electron in one layer is always opposite a hole in the other layer. It is not implausible that this interlayer correlation enhances tunneling. This simplistic view, while appealing, does not address the sharply resonant nature of the enhancement. The experimental observation of a narrow peak in the tunneling conductance at zero interlayer voltage suggests that there is a collective mode near zero energy which can transfer charge between the two layers. The predicted pseudospin Goldstone mode does exactly this. This mode involves oscillations of the pseudospin magnetization both in the xy-plane and in the z-direction of pseudospin space. This latter component resembles an antisymmetric interlayer plasma oscillation. In the absence of tunneling no charge is transferred between the layers and the mode energy vanishes in the long wavelength, $q = 0$ limit. In a real sample however, the finite tunneling amplitude leads to an energy gap at $q = 0$ and, most importantly, allows the collective mode to transfer charge. The estimated gap ($\sim$ 70mK=6μeV) is much smaller than the observed width of the tunnel resonance (typically 150μeV at low temperature) so it is not surprising that a single peak in dI/dV appears at V=0. From this point of view, tunneling appears to provide direct spectroscopic evidence for the Goldstone mode of the broken symmetry QHE state at $\nu_T = 1$.

In conclusion, we have examined tunneling in double layer 2D electron systems in which interlayer correlations are very strong. A dramatic resonant enhancement of the zero bias tunneling conductance is observed when the system crosses the phase boundary from a compressible fluid into the $\nu_T = 1$ ferromagnetic quantized Hall state. Although detailed understanding of the tunnel spectra is lacking, it seems likely that the observed resonance is intimately connected with the Goldstone mode of the broken symmetry state.

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